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Review of the ergonomic design and development and performance evaluation of solar-cum-pedal powered thresher

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Abstract
Threshers are crucial for post-harvest paddy management, specifically for separating grain from the plant. Farmers face significant challenges in transporting and using complex threshers, such as combine harvesters or multi-crop threshers, particularly in rural or hilly areas. To address these issues, there is a need for a design and development of low-cost, easily transportable thresher designed for small and marginal farmers. This review focuses on the design, development, and evaluation of pedal-operated paddy threshers, adhering to the specifications outlined in BIS 3327: 1982. The conventional four-bar linkage mechanism in pedal-operated threshers demands significant effort during operation. Solar photovoltaic systems present an effective alternative power source for threshing machines, especially in areas with limited or no electricity supply. This review evaluates the performance of a thresher based on physiological parameters, specifically heart rate and energy expenditure rate. It was found that the pedal-operated paddy threshers exhibit the most favourable configuration, with the lowest working pulse rate of 45.90 bpm and an energy consumption rate change of 214.5 W (12.87 kJ min^{-1}).

Keywords: Threshers, post-harvest paddy management, grain separation, pedal-operated thresher

Introduction

Threshing plays a critical role in the post-harvest processing of paddy by removing grains from the plant through various methods such as rubbing, treading, or striking. Different types of threshers, including drum type, spike tooth cylinder type, rasp bar cylinder type, hammer mill type, and syndicator type, are used in India for various crops. These threshers operate through mechanisms like loop type, rasp bar, peg tooth, and hammer mill, and can be either manual or mechanical. In rural India, manual methods are prevalent, with pedal-operated threshers being common. However, traditional pedal threshers often lack cleaning facilities and require separate winnowing. With 85-90% of global energy derived from fossil fuels and a rising trend in fuel prices, many rural areas, where electricity and non-renewable energy sources are scarce or expensive, need affordable and simple threshers that are easy to transport and maintain. Research comparing the efficiency of arm and leg exercise is limited. Powers *et al*. (1984) [13] conducted an experimental study to investigate the effects of speed and work rate on efficiency during arm exercise on an ergometer. Ten male participants exercised at speeds of 50, 70, and 90 rpm with power outputs of 15, 30, 45, and 60 W. The study revealed a curvilinear relationship between work rate and energy expenditure, indicating that both delta efficiency and work efficiency decrease with increased workload. Work efficiencies ranged from 20% to 29%, while delta efficiencies varied from 14% to 30%. The results indicated that gross efficiency increased by 6% to 15% with increased workload, attributed to the diminishing influence of the resting metabolic rate on total energy expenditure. Notably, both gross work and delta efficiencies were significantly lower at 90 rpm compared to 50 and 70 rpm. Although efficiencies at 70 rpm were lower relative to those at 50 rpm, significant differences were only observed at higher workloads. This suggests that while power output increases, efficiency decreases with higher speeds during arm crank exercise. the calibration of physiological parameters, particularly heart rate and oxygen consumption, is an essential process for assessing workload in operational tasks. Numerous studies confirm a linear relationship between heart rate and oxygen consumption, making heart rate a practical proxy for estimating energy expenditure, especially in field conditions.

Despite individual variations due to fitness levels, heart rate calibration offers a reliable method to monitor and evaluate metabolic activity across varying workloads. Solar photovoltaic systems offer a viable alternative for powering threshing machines used in paddy cultivation, particularly in regions lacking reliable electricity. However, when solar energy is unavailable due to weather conditions, an additional pedal unit becomes necessary to ensure continuous operation in the field. Existing four-bar linkage mechanisms for pedal-operated threshers require considerable effort for operation. Chain mechanisms allow rotation of the threshing cylinder in one direction only, eliminating the need for initial momentum to start the drum (Patel, 2015) [3, 15]. Furthermore, current threshers lack adjustable mechanisms for pedal and thresher height, necessitating the use of manual or mechanical threshers for farmers in these conditions.

Methods and Methodology

Design and Development

Singh *et al*. (2008) [21] designed and developed the VL pedal-operated paddy thresher, which utilizes a human-powered pedal chain drive mechanism. The performance evaluation of this machine focused on optimizing design parameters, including a wire loop length of 39.1 mm, a wire loop tip height of 60.6 mm, and a threshing drum speed of 270.1 rpm. For the Thapa Chini variety, the thresher achieved a capacity of 64.6 kg/hr and an efficiency of 98.3%.
Gadhe *et al*. (2016) [22] developed and assessed a thresher operating at three different cylinder speeds (9.63, 11.72, and 13.83 m/s), three feed rates (200, 400, and 500 kg/hr), and two grain moisture levels (13.5% and 16% wet basis). The optimal operating parameters were determined based on the test results. The thresher, operated at a cylinder speed of 13.83 m/s, a grain moisture level of 13.5%, and varying feed rates, demonstrated the best performance in terms of threshing efficiency, cleaning efficiency, and minimal grain loss.
Sureshkumar (1996) [14] designed a low-cost, power-operated wire loop paddy thresher cum winnower, adhering to BIS 3327: 1982 specifications. The machine, powered by a 2 hp electric motor, had a capacity of 300 kg/h with threshing and cleaning efficiencies of 99.25% and 91.82%, respectively.
Patel (2015) [3, 15] improved a pedal-operated paddy thresher using digital models to prevent musculoskeletal disorders. The study recommended an optimal thresher height of 81 cm for workers in the 5th to 95th percentile of the North-East population.
Baruah and Pankaj (2018) [16] developed a pedal-powered thresher using a four-bar transmission mechanism, where the pedal’s reciprocating motion is converted to rotational motion for threshing.
Mutai *et al*. (2018) [17] designed a pedal-powered paddy thresher with winnowing equipment, reducing human effort and operating at 400 rpm with a power consumption of 84 watts. The machine's output was 90 kg/hr with 92% efficiency.
Parmanand *et al*. (2015) [12, 18] created a pedal-operated thresher for finger millet with a spike-tooth threshing cylinder, capable of winnowing premature grains and leaves.
Dickson (2017) [19] evaluated both hand and foot-operated threshers, finding that the foot-operated Konongo thresher had a higher average output rate of 22.52 kg/hr compared to the hand-operated Fomena thresher’s 12.45 kg/hr.
Amare *et al*. (2015) [20] developed a pedal rice thresher with a chain drive mechanism, achieving a threshing output of 127.5 kg/hr, which was more efficient compared to traditional methods. This thresher reduced labor demand by 77.08% and saved Rs. 714.93 in costs.
Akshay *et al*. (2018) [23] developed a solar-operated through-flow thresher, but faced challenges with transportation, requiring at least six people to move the machine.

Arm vs. Leg Exercise

Kang *et al*. (1997) [25] explored metabolic efficiency during arm and leg exercises at equivalent relative intensities. They concluded that metabolic efficiency, measured through functional and delta efficiency indices, is comparable between arm crank and cycling exercises. Faria and Faria (1998) [26] similarly found that cardiovascular responses during sub-maximal exercise did not differ significantly between upper and lower body activities, provided the workloads were matched for intensity. However, Sawka (1986) [27] noted that upper body (arm) exercise incurs a higher physiological cost than lower body (leg) exercise. Pendergast (1989) [28] confirmed that the maximum aerobic capacity achieved in arm exercise is typically lower than in leg exercise, with sub-maximal power production being higher in the upper body.

Pedal Rate and Energy Expenditure

Weissland *et al*. (1999) [29] reported optimal pedal rates that correlate with total energy expenditure, highlighting significant variability among participants during cyclic activities. Marsh and Martin (1993) [25] suggested that this optimal pedal rate may depend on muscle mass and specific exercise protocols. Human energy is commonly utilized in operating various agricultural machines, primarily using the upper limbs. However, lower limbs are also employed for tasks such as water pumping and sprayer operation, often resulting in less fatigue compared to hand operations. Ergonomic assessments have been conducted to evaluate limb function in these contexts.
Demonstrated a linear relationship between workload and energy expenditure, showing that pedaling with the legs required less energy than using the arms at equal workloads. Astrand (1965) [32] studied 44 females across different age groups, finding minor variations in oxygen consumption during pedaling at a constant speed. The relationship between workload and oxygen uptake was linear with a positive correlation. Examined various pedal speeds and workloads, finding that oxygen consumption increased linearly with power output. Subsequent studies by Faria *et al*. (1982) [26] also reported significant increases in oxygen uptake with higher power outputs across different pedal speeds.

Human-Powered Systems

Modak and Khope (2013) [30] developed a Human Powered Flywheel Motor (HPFM) for cutting agricultural residues, demonstrating that leg muscles are stronger than arm muscles. This pedal-powered system stores energy in a flywheel, which is then used to operate agricultural tools efficiently. Further developed a bicycle chain drive mechanism to transform human energy into mechanical energy for various manually operated machines. Reported that HPFM setups can enhance rotary power generation through pedaling. Reddy *et al*. (2016) [31] investigated energy requirements for pedal-operated threshers, noting that flywheels serve as storage devices for rotational energy.

Age-Related Performance Factors

Several studies have highlighted the decline in VO_2 max, muscle strength, and overall performance with age. Astrand *et al*. (1965) [32] found that peak VO_2 max occurs between ages 18 and 20. Grandjean (1982) [33] established a correlation between age and oxygen consumption rates, noting that maximum performance is typically seen in individuals aged 20 to 30 (Table 1). Identified that male workers aged 16 to 30 performed best in harvesting tasks, while Varghese *et al*. (1995) [34] indicated a positive relationship between VO_2 max, body weight, and age.

Table 1: Performance percentage with respect to age

SL. No	Age(years)	Maximum performance (%)
1	60 – 65	75
2	50 – 60	80
3	40 – 50	90
4	30 – 40	9
5	20 – 30	100

Calibration of Subjects and Body Part Discomfort Score (BPDS)

Physiological factors, such as heart rate and oxygen consumption, play a crucial role in assessing workload during operations. The process of calibrating subjects involves establishing the relationship between each individual's working heart rate and their oxygen consumption. This calibration is essential for determining physiological workload, as heart rate can be referenced from calibration charts during experiments. A linear relationship exists between heart rate and oxygen consumption (Astrand & Rodahl, 1977; Sanders & McCormick, 1993; Kroemer *et al*., 1997; Rodahl, 1989; Nag *et al*., 1988) [35, 42, 37, 40]. Since measuring oxygen consumption directly can be challenging, calibration is typically conducted up to a sub-maximal point in a controlled laboratory setting.

Calibration charts are then created to estimate energy consumption. Astrand and Rodahl (1977) [35] noted that heart rate could be calculated based on workload, confirming the linear correlation between heart rate and oxygen consumption. The extrapolation method allows for the determination of mean heart rate and oxygen consumption values. Rodahl (1989) [41] emphasized the significance of this linear relationship in setting physiological parameters, while Sanders and McCormick (1993) [42] highlighted that heart rate is the best indicator of oxygen consumption during moderate to heavy workloads. Kroemer *et al*. (1997) [33] noted that heart rate and oxygen consumption can vary for individuals, especially among those with differing fitness levels, making heart rate a convenient measure for evaluating metabolic processes.

In addition to physiological factors, different body parts experience varying levels of discomfort due to postural stresses, which depend on factors such as position, force application, and duration of activity. Several techniques have been developed to assess the Body Part Discomfort Score (BPDS). Corlett and Bishop (1979) [36] introduced a body mapping technique to identify postural pain at work, illustrating how discomfort is distributed across the body and how it changes throughout tasks. Their method involved dividing the body into 27 regions and asking subjects to indicate areas of discomfort, starting from the most painful.

Kroemer and Grandjean (2000) [38] described fatigue symptoms as general feelings of tiredness, including decreased alertness, weakness, and reduced work capacity. Various studies have applied this technique to ergonomically evaluate discomfort associated with farm machinery operation (Tondon & Kumar, 1995; Kumar *et al*., 2002; Tiwari *et al*., 1991) [44, 39, 43].

Performance Evaluation

Srikanthnaik *et al*. (2021) [45] The performance of a solar-cum pedal operated paddy thresher was evaluated in field conditions (Fig.1). During the threshing process, an optimal drum speed of 290–310 rpm was achieved with 21 pedal strokes. The paddy was threshed at a moisture content of 18.45%, with the thresher achieving a threshing efficiency of up to 99%. Optimal paddy holding capacities of 0.5 kg, 1 kg, and 0.75 kg were recorded, with the ideal foot pedal size being 14.35 cm and the optimal threshing cylinder height being 101.25 cm. In solar mode, the thresher's efficiency ranged from 99.58% to 98.67%, compared to 98.54% to 97.01% in pedal mode. The solar-powered threshing rate was 231.67 kg/h, significantly higher than the 66.63 kg/h achieved in pedal mode—making the solar mode 3.47 times more efficient. This thresher is particularly beneficial for small-scale farmers in rural areas where electricity is unavailable or unreliable. Its lightweight design also makes it ideal for farmers in hilly regions, as it can be easily transported.

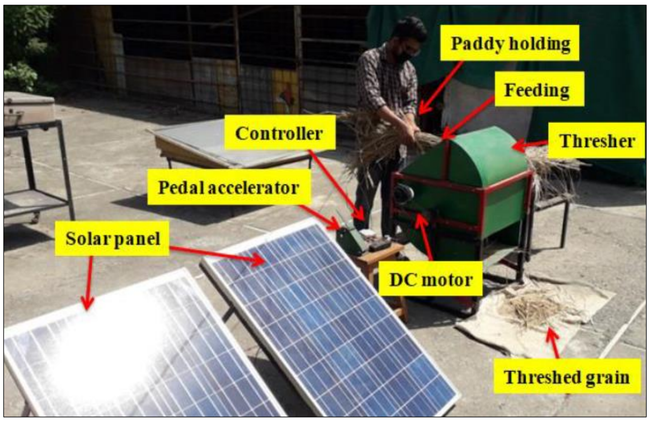

Fig 1: Evaluation of a solar-cum pedal operated paddy thresher

Ramachandra *et al*. (2011) [1] highlighted India's potential for solar power generation, noting that approximately 58% of its land area (1.89 million km²) receives an average annual global insolation exceeding 5 kWh/m²/day. Present efficiency rates suggest that 1% of this land area could meet India's energy needs by 2031. Solar radiation intensity in India averages 200 MW/km², with 250-325 sunny days annually. Regions like Rajasthan and northern Gujarat experience the highest annual global radiation (2400 kWh/m²).

Veeraboina and Ratnam (2012) [2] estimated India's solar potential at around 5000 trillion kWh per annum, significantly exceeding current energy requirements. The solar radiation incident on India is about 4-7 kWh per square meter per day, with an annual total of 1200-2300 kWh per square meter. India experiences 250-300 bright sunny days each year, with 2300-3200 hours of sunshine. The solar power available is substantially higher than both the current global annual energy consumption average of approximately 15 TW and future energy demands. Solar power is a renewable, environmentally friendly source with no harmful by-products or pollution. Currently, India generates 4.59% of its total renewable energy from solar sources.

Anonymous (2016) developed a motor-cum-pedal operated arecanut dehusker, which could operate using both pedal and motor power, achieving capacities of 9.8 kg/hr and 13 kg/hr respectively. Anonymous (2017) created a motor-cum-pedal operated grain cleaner with a capacity of 330-800 kg/hr, costing Rs. 8500/-. Ologunagba *et al.* (2010) [6] designed a dual-powered palm fruit stripper, which, when operated manually, had a capacity of 0.612 tonnes/hr, and with an electrical motor of 2.25 kW, the efficiency improved to 2.14 tonnes/hr. Ndaliman (2006) [7] developed a dual-powered cassava grating machine, which could be operated manually or electrically, demonstrating efficiencies of 92.4% and 91.9%, respectively. Anonymous (2016) also developed a manual-cum-motor operated chaff cutter with a capacity of 200-400 kg/hr, priced under Rs. 9,500/-, suitable for small dairy farmers.

Kwatra *et al.* (2010) [9] compared paddy threshing operations by farm women using manual beating on a wooden platform versus manually controlled threshers. The mean heart rate for manual paddy beating was 154.5 bpm, while it was 122.5 bpm with threshers, showing a 20.71% reduction in heart rate. The energy expenditure rate (EER) was 17.64 kJ/min for manual beating and 12.80 kJ/min with threshers, with total cardiac labor costs (TCCW) and physiological labor costs (PCW) decreasing by 60.28% with threshers. Suggestions for improving thresher design were proposed.

Agrawal *et al.* (2012) [10] explored alternative thresher drive-link designs to determine their impact on the load application pattern and physiological workload. The most promising configuration showed a low working pulse rate of 45.90 bpm and an energy consumption rate change of 214.5 W (12.87 kJ/min). Khadatkar *et al.* (2018) [11] assessed a pedal-operated paddy thresher with 12 female farmers and compared it to conventional manual paddy beating. The mean working heart rate for the pedal thresher was 134 bpm compared to 141 bpm for manual beating, with an energy expenditure rate of 17.71 kJ/min for threshers versus 19.34 kJ/min for conventional methods. The production rate with the paddy thresher increased by 20%, and drudgery was reduced by 43% compared to conventional methods. Parmanand *et al.* (2015) [12, 18] evaluated the performance of a pedal-operated finger millet thresher, finding average working heart rates between 116-129 bpm and energy expenditure rates from 14 to 17.8 kJ/min.

Conclusion

The review indicates that India's substantial solar generation capacity can be effectively utilized for paddy threshing, offering a cost-effective and emission-free energy source. The performance of solar-cum-pedal powered threshers, assessed through physiological parameters such as heart rate and energy expenditure, shows that pedal-operated threshers are highly efficient. The most promising configuration features the lowest working pulse rate of 45.90 bpm and an energy consumption rate change of 214.5 W (12.87 kJ/min), highlighting their potential for improving agricultural efficiency and reducing operator strain. The reviewed studies consistently focus on pedal-operated threshers driven by human-powered mechanisms, comprising four key components: feeding, threshing, cleaning, and power transmission. Efforts to design and improve these threshers follow the BIS 3327: 1982 standards, emphasizing ergonomic design, efficiency, and cost-effectiveness. The pedal-operated threshers address the needs of small and marginal farmers by providing a low-cost, accessible, and practical solution for post-harvest paddy management.

This review emphasizes the differences in metabolic and exercise efficiencies between upper and lower body activities, underscoring the influence of age and physical capacity on performance. Simultaneously, the Body Part Discomfort Score (BPDS) provides a valuable ergonomic assessment of how different body regions are impacted by physical tasks. Techniques like body mapping allow for detailed tracking of postural discomfort and fatigue symptoms, contributing to a better understanding of the physical demands placed on workers in various occupational settings. Together, these methods—physiological calibration and discomfort mapping—offer a comprehensive approach to managing both the metabolic and ergonomic demands of operational tasks, ultimately enhancing safety, performance, and well-being in the workplace. Further investigation is needed to explore the practical implications of these findings, particularly regarding the design of human-powered systems and ergonomic assessments in labor efficiency.

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